Solar Insolation and Earth Radiation Budget Measurements

Topics:
1. Daily solar insolation calculations
2. Orbital variations effect on insolation
3. Total solar irradiance measurements
4. ERBE and Earth radiation budget measurements

Reading: Liou 2.2-2.3, 8

Solar Insolation

Practical solar flux calculations require knowledge of the solar zenith angle for any location, time of day, and day of year.

Earth-Sun geometry and solar insolation:

The top of the atmosphere (TOA) solar flux is

$$F(t) = S_0 \left(\frac{r_0}{r}\right)^2 \cos\theta_0 \ ,$$

where S_0 is the solar constant at the mean Earth-Sun distance r_0, and θ_0 is the solar zenith angle. The Earth-Sun distance r varies throughout the year according to the elliptical orbit.

Solar Zenith Angle and Day Length

From spherical trigonometry the solar zenith angle depends on the latitude ϕ, declination of the Sun δ, and hour angle h

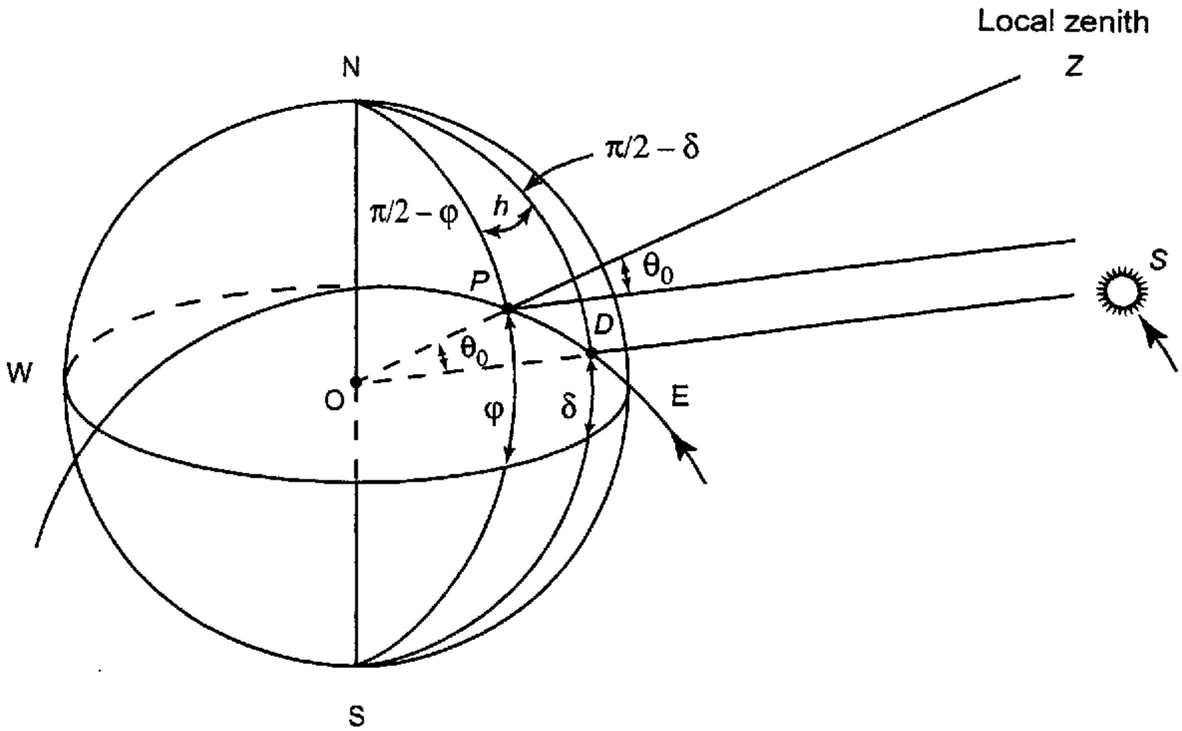
$$\cos\theta_0 = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h$$

The hour angle is 0 at solar noon. The declination varies from -23.5° at the northern winter solstice to 23.5° at the northern summer solstice.

The hour angle at sunset H when $\theta_0 = 90^\circ$ is then

$$\cos H = -\tan\phi \tan\delta$$

The length of a day is (24 hr)H/π.



Relationship of the solar zenith angle θ_0 to the latitude ϕ, the solar inclination angle δ, and the hour angle h. P and D are the point of observation and the point directly under the Sun, respectively. [Liou; Fig. 2.5]

Solar Declination

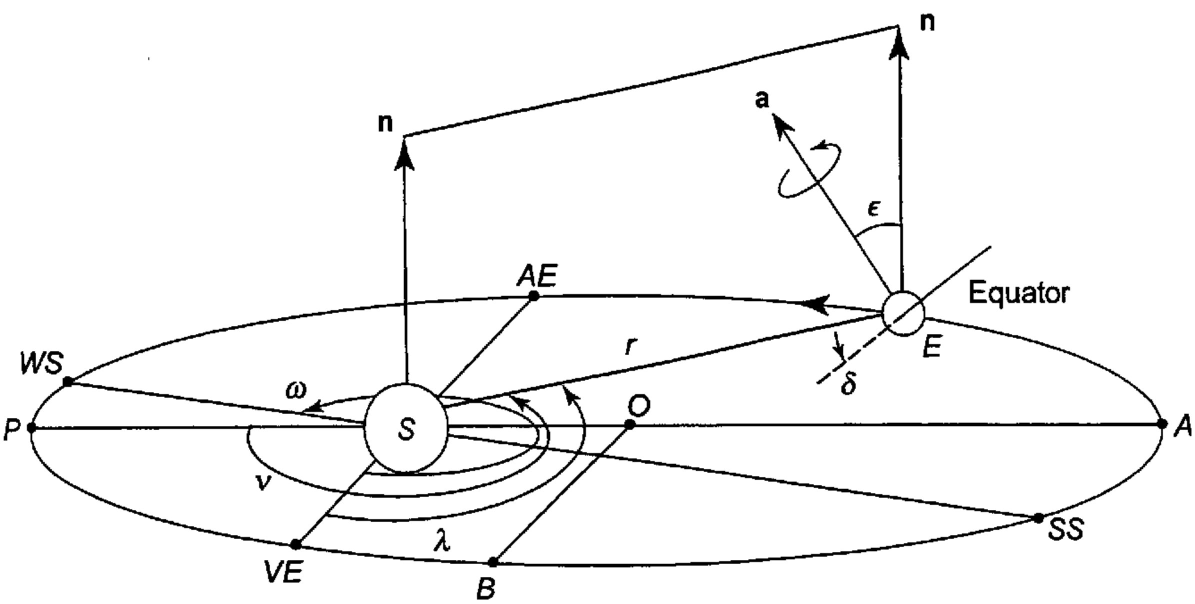
The solar declination varies throughout the seasons according to

$$\sin\delta = \sin\epsilon\sin(\nu+\omega) = \sin\epsilon\sin\lambda\ ,$$

where ϵ is the obliquity or tilt of the earth's axis,
ω is the longitude of the perihelion relative to the vernal equinox,
ν is the true anomaly, the angle from the perihelion, and
$\lambda = \nu + \omega$ is the longitude of the Earth from the vernal equinox.

The true anomaly, $\nu = \lambda - \omega$, varies from 0 to 2π over the year (0 at perihelion) and is determined as a function of time from Kepler's laws.

For an approximately circular orbit, the longitude of the Earth is linear in time, $\lambda \approx 2\pi t_v/T,$ where t_v is the time from the vernal equinox and $T = 365.2422$ days is the orbital period.



The Earth-Sun geometry. P denotes the perihelion, A the aphelion, AE the autumnal equinox, VE the vernal equinox, WS the winter solstice, SS the summer soltice; **n** is normal to the ecliptic plane; **a** is parallel to the Earth's axis; δ is the declination of the Sun, ϵ is the oblique angle (tilt) of the Earth's axis, ω is the longitude of the perihelion relative to the vernal equinox, O the center of the ellipse, $OP = OA = a$ the semi-major axis, $OB = b$ the semi-minor axis, S the position of the Sun, E the position of the Earth, and $ES = r$ the distance between the Earth and the Sun. [Liou; Fig. 2.4]

Earth-Sun Distance

The Earth-Sun distance varies throughout the year according to Keplers Law:

$$r = \frac{a(1-e^2)}{1+e\cos\nu}$$

where e is the eccentricity of the orbit and a is the semimajor axis.

For an approximately circular orbit $e \ll 1$, and

$$r \approx r_0[1 - e\cos\nu] \ \approx r_0[1 - e\cos(2\pi t_p/T)]$$

where t_p is the time from the perihelion.

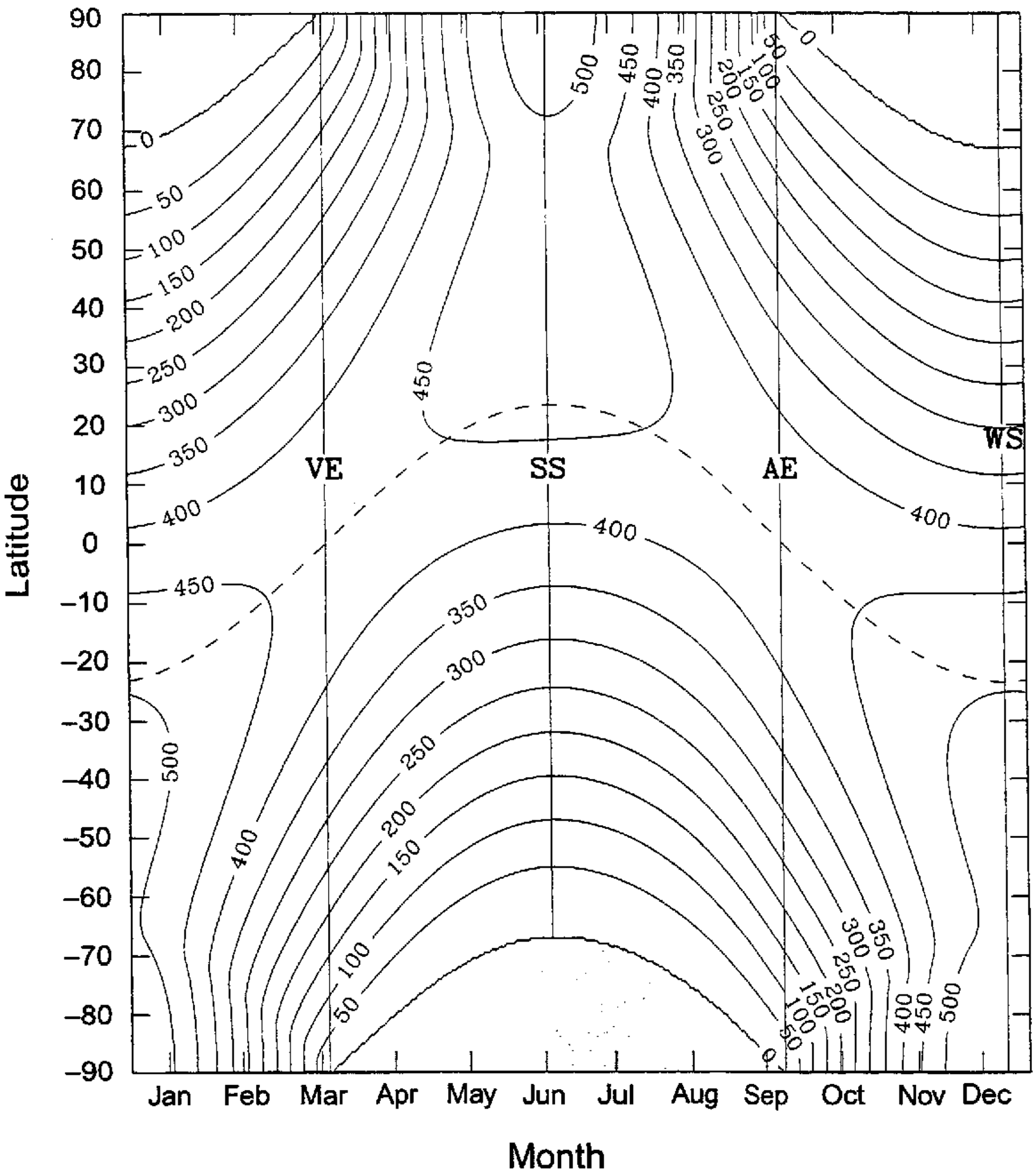
Daily Insolation

The daily solar insolation at the top of the atmosphere is found from integrating the instantaneous solar flux over a day assuming that r and δ don't change significantly:

$$\bar{F} = S_0\left(\frac{r_0}{r}\right)^2 \int_{-H}^{H} \cos\theta_0 \frac{dh}{2\pi}$$

$$\bar{F} = \frac{S_0}{\pi}\left(\frac{r_0}{r}\right)^2 (H \sin\phi \sin\delta + \sin H \cos\phi \cos\delta)\ .$$

The daily insolation as a function of time of year and latitude is plotted below.



Daily solar insolation as a function of latitude and day of year in units of W/m^2 based on a solar constant of 1366 W/m^2. The day of the vernal equinox (VE), summer solstice (SS), autumnal equinox (AE), and winter solstice (WS) are indicated with solid vertical lines. Solar declination is shown with a dashed line. [Liou; Fig. 2.7]

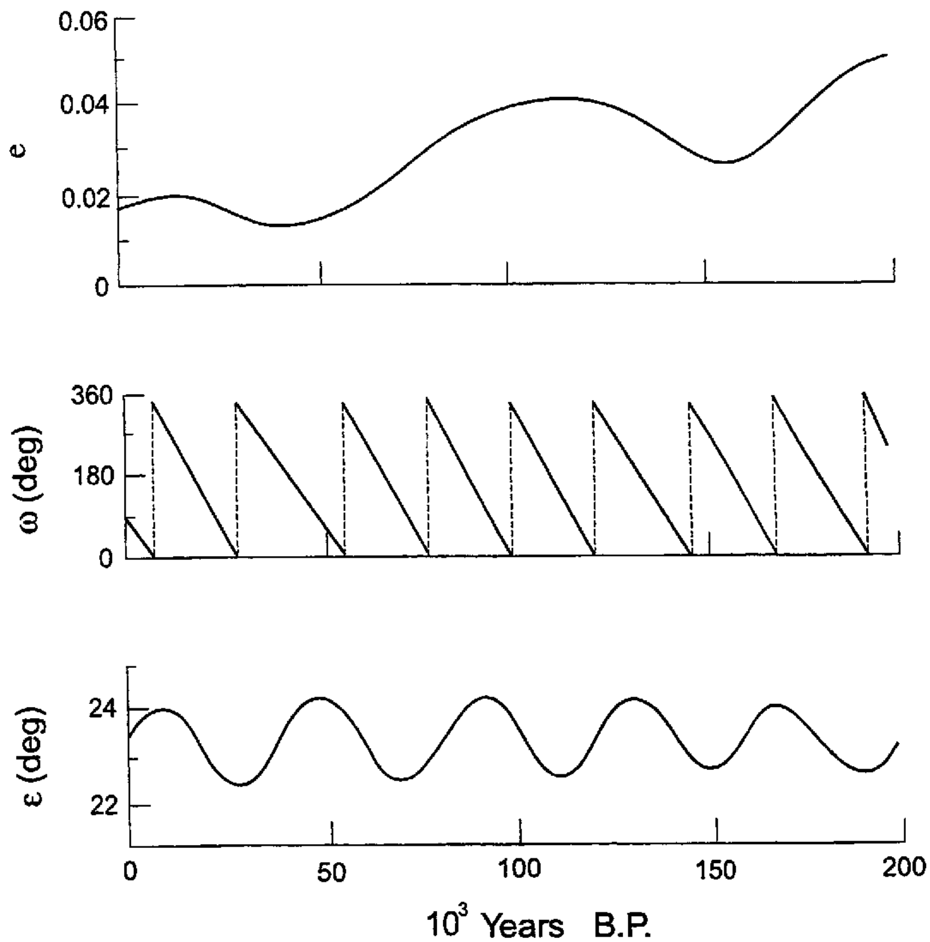
Orbital Parameters

Three orbital “constants” determine insolation.

These parameters are constant for < 100 years, but vary over thousands of years.

	Parameter	today	range	cycle
ϵ	obliquity (tilt)	$23.5°$	22.0 - 24.5	41 kyr
e	eccentricity	0.017	0 - 0.06	90 kyr
ω	longitude perihelion	$283°$(Jan 3)	0 - 360	21 kyr

Obliquity controls seasonality.
Eccentricity controls range of Earth-Sun distance.
Longitude of perihelion controls timing of perihelion/aphelion.



The eccentricity e, obliquity ϵ, and longitude of the perihelion ω of the Earth as a function of year before present. [Liou; Fig. 2.6]

Milankovitch Theory

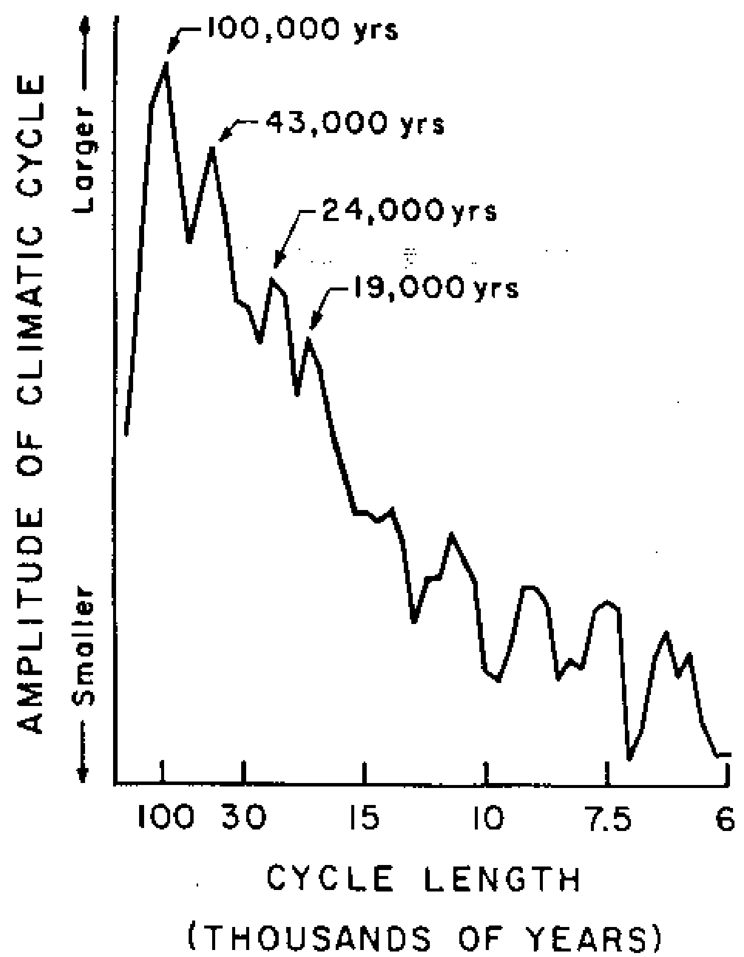
In 1920's Milankovitch developed the theory that variations in orbital parameters cause ice ages.

Concept: Northern summer high-latitude insolation is critical to triggering ice ages. Less summer-time insolation causes less melting, expansion of northern hemisphere ice sheets.

Northern summer-time insolation minimized by:

1) large eccentricity, 2) aphelion in summer, and 3) small obliquity.

Global ice volume histories reconstructed from oxygen isotope ratios in deep sea cores show spectral peaks at the orbital forcing frequencies.

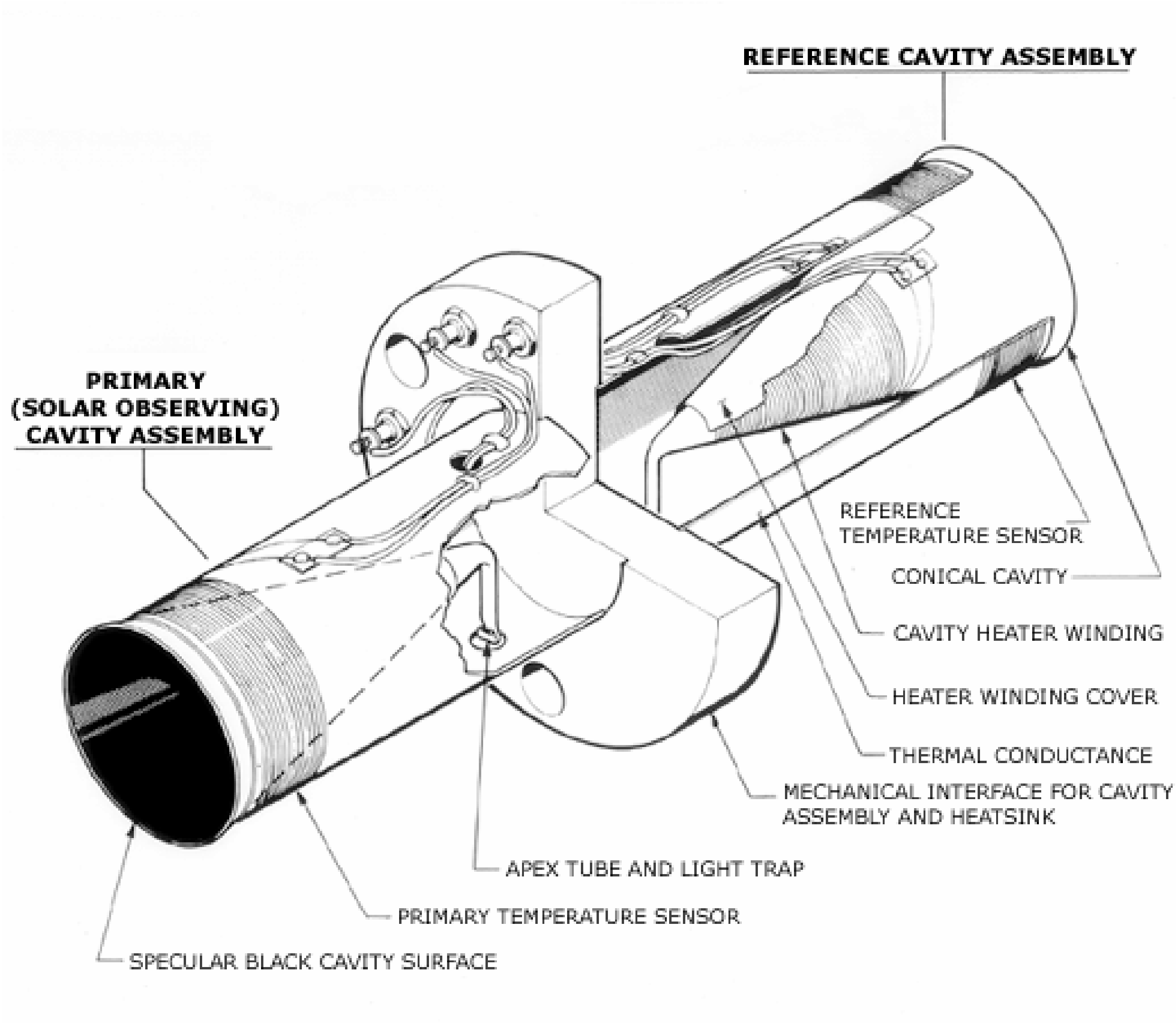


Spectrum of climate variation over the past half-million years. This graph, showing the relative importance of different climatic cycles in the isotopic record or two Indian Ocean cores, confirmed many predictions of the Milankovitch theory. [data from J. D. Hayes et al., 1976]

Total Solar Irradiance measurements (TSI):

Active cavities in space provide very accurate, stable measurements of broadband solar flux (also used for ERB and pyrheliometers).

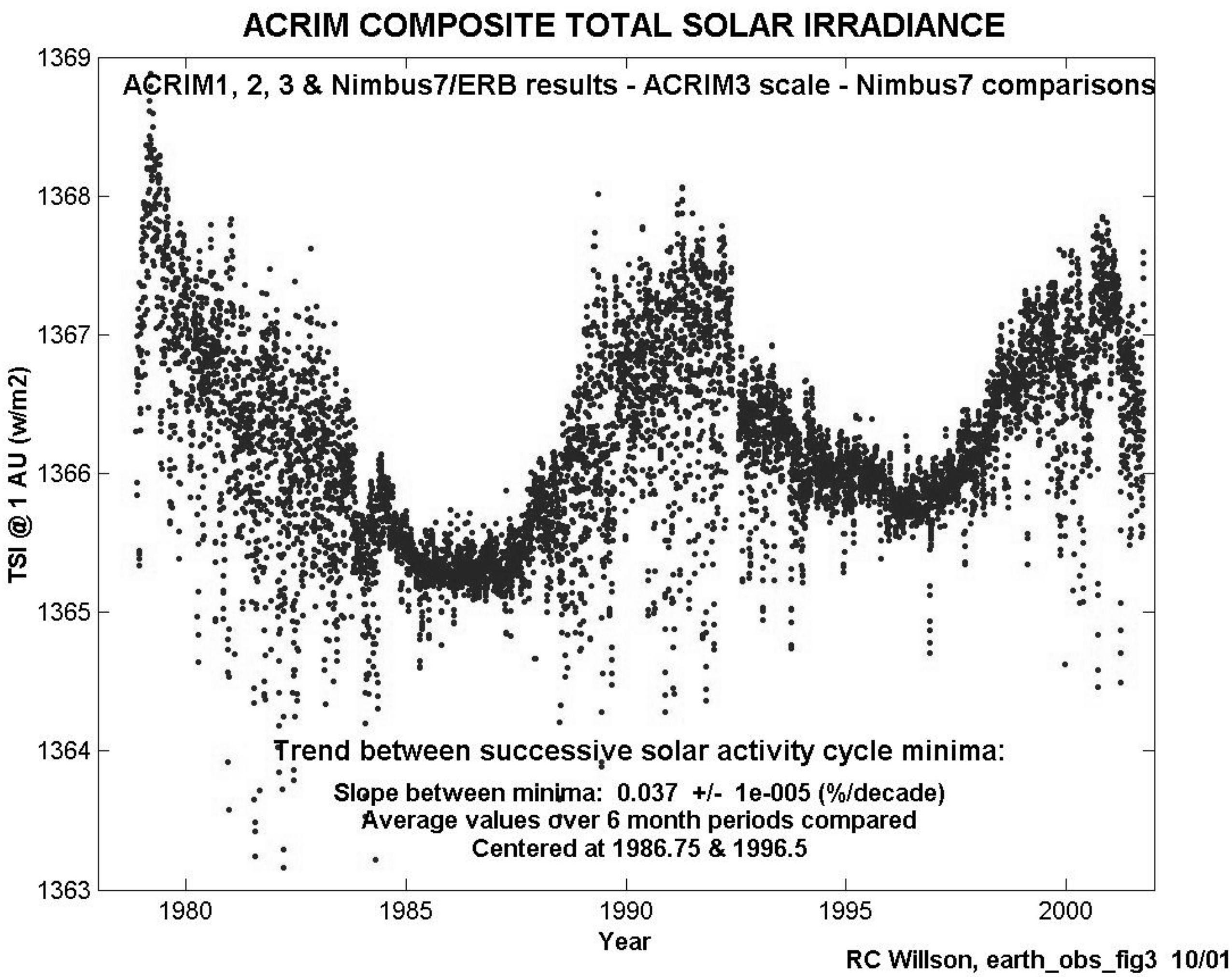
Measurement principle: absorb flux in blackbody cavity and add electrical resistive heating to maintain same temperature as electrically heated reference cavity. Conversion to SI units through amount of electrical power required to balance.



Active Cavity Radiometer (ACR) type V sensor design.

Space measurements over the 20 years show a variation of about $\pm 0.1\%$ (≈ 3 W/m^3 range) in solar flux over the 11-year solar magnetic cycle. The individual ACRIM instruments have absolute accuracies about ± 4 W/m^2, but precisions of 0.0005% (<0.01 W/m^2). There is substantial daily variation in solar flux due to sunspot activity and solar rotation.

The TSI variations are well correlated with sunspot number and 10.7 cm radio flux indicators of solar magnetic activity. These correlations have been used to extrapolate solar irradiance to earlier times (e.g. the Maunder minimum of sunspots in 1600's).



More than two decades of total solar irradiance measurements.

Earth Radiation Budget Measurements

- Earth Radiation Budget measurements from space provide the top of atmosphere radiative boundary conditions.
- The goal is to measure TOA absorbed shortwave and emitted longwave fluxes on a regional scale.
- ERB measurements are used to
  1) understand actual radiative effects of clouds, aerosols, and trace gases,
  2) to evaluate clouds and radiation in climate models.

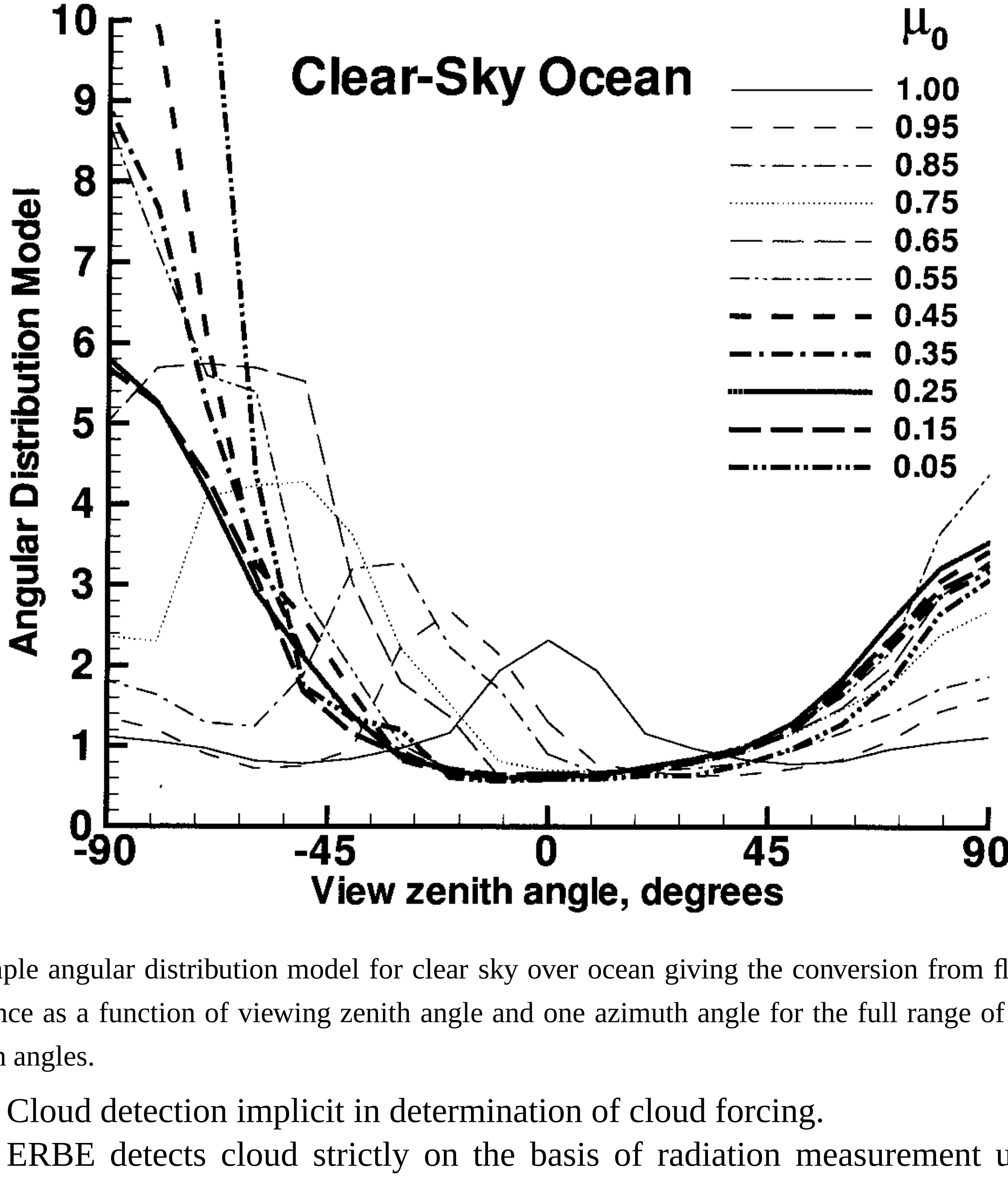
Earth Radiation Budget Experiment (ERBE)

- First instrument launched on ERBS satellite in 1984 in
  56° inclination orbit for full diurnal coverage.
- Two additional instruments on NOAA satellites for better sampling.
- Scanner looks at relatively small regions (~ 50 km) at many angles. Allows separation of clear and cloudy regions for cloud radiative ”forcing”.
- Nonscanner looks at large regions:
  No clear/cloudy discrimination, but still working after 15 years!
- Three broadband channels: SW, LW, Total (total = SW + LW?).

Key Components of ERB Measurement Systems

- Calibration of instrument is CRUCIAL:
  Done using deep space and on-board calibration reference.

- Diurnal sampling needed: surface temperature cycle & cloud changes throughout the day.
- Angular modeling: actually measure radiance in the direction viewed by the spacecraft, but want TOA flux.
  ERBE uses empirical approach, assimilating lots of measurements to get a mean pattern of radiance (ADM) for different scene types.



Example angular distribution model for clear sky over ocean giving the conversion from flux to radiance as a function of viewing zenith angle and one azimuth angle for the full range of solar zenith angles.

- Cloud detection implicit in determination of cloud forcing.
  ERBE detects cloud strictly on the basis of radiation measurement using Maximum Likelihood Estimation: clouds are cold (low LW) and bright (high SW). Four categories of cloud cover (0-100%).

ERBE Regional Results

Errors reduced by averaging TOA fluxes to monthly $2.5 \times 2.5°$ boxes.

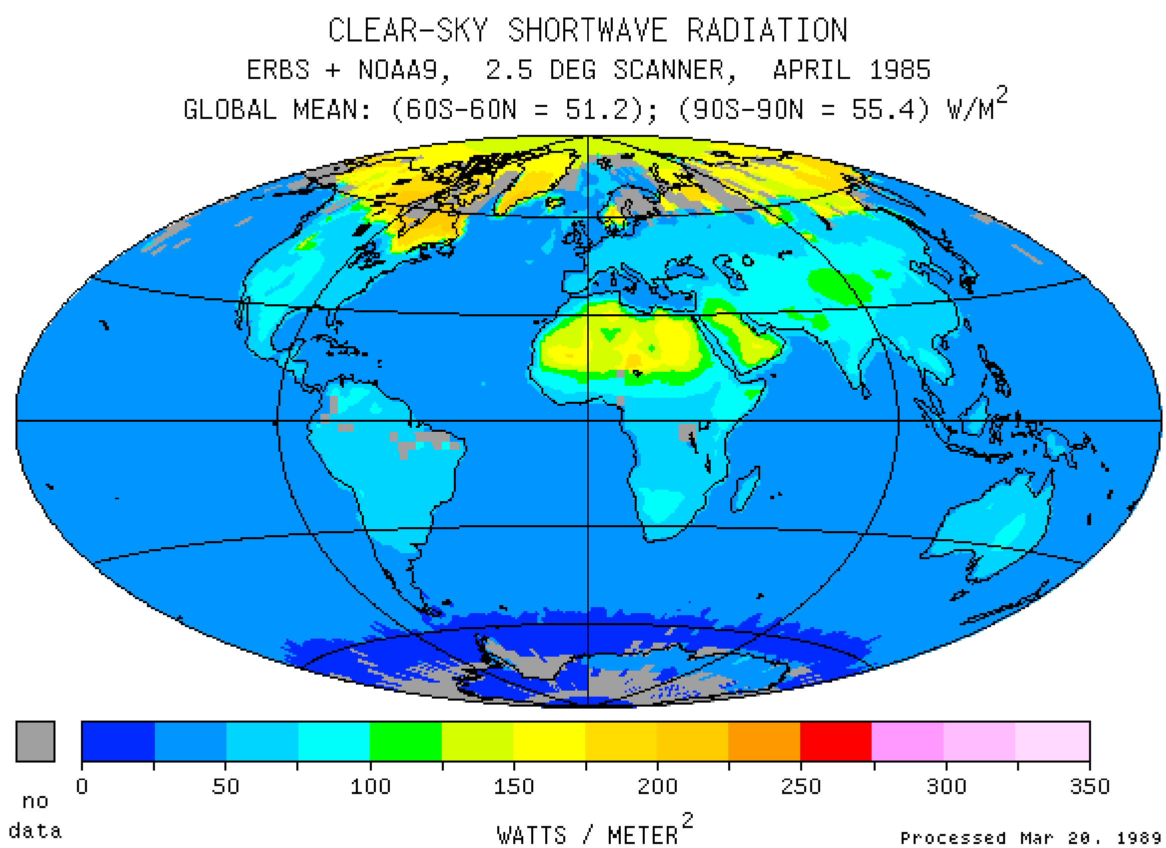
Reflected shortwave flux depends on TOA solar insolation and albedo.
Albedo lowest for clear ocean; high for snow/ice surfaces,
bright deserts, and persistently cloudy regions.

Outgoing longwave radiation (OLR) high for warm clear sky regions;
low for cold polar and high cloud regions.

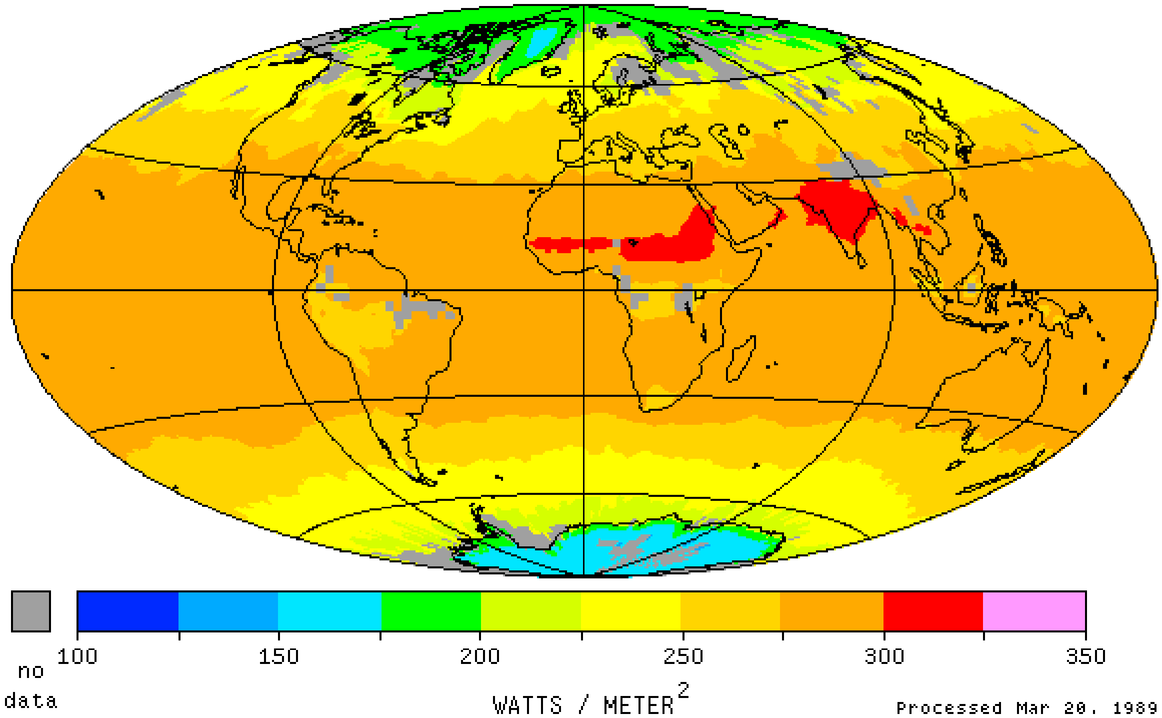
Cloud radiative "forcing" - difference between clear and total fluxes:

$$C_{LW} = F_{LW}^{clr} - F_{LW} \qquad C_{SW} = \mathcal{S}(r^{clr} - r)$$

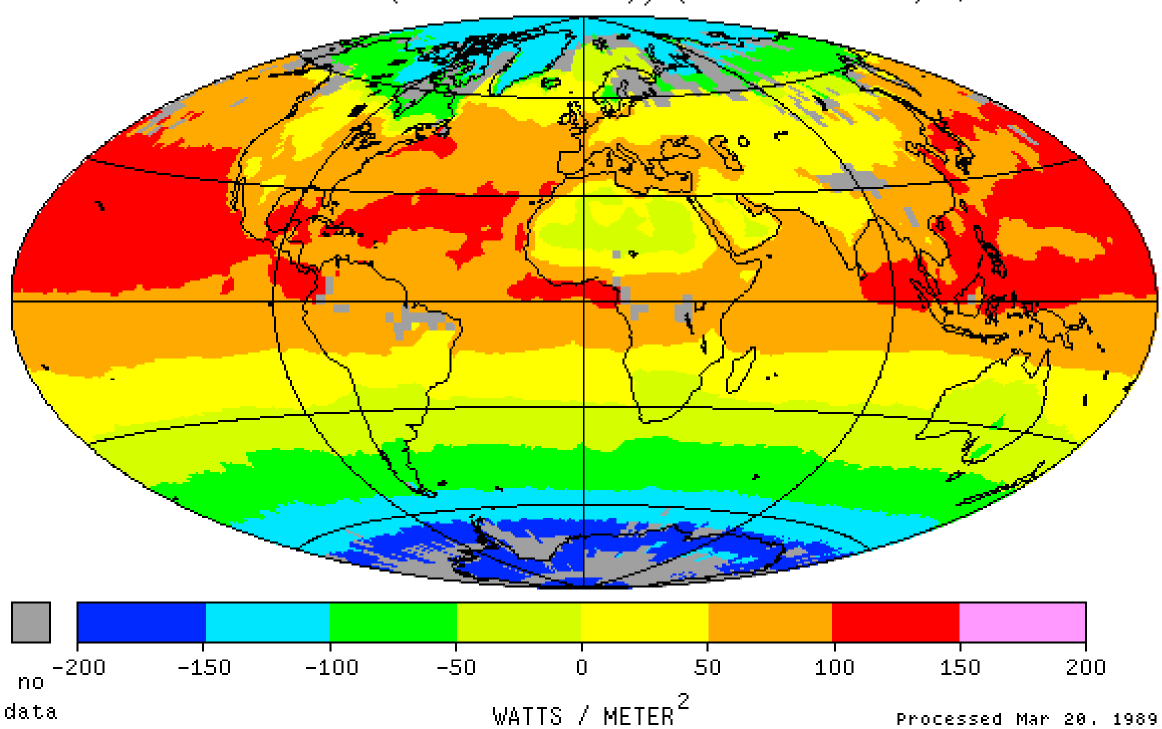
$\mathcal{S}$ is TOA solar insolation, r is albedo, and F_{LW} is outgoing LW flux.
$C_{LW} > 0$ clouds reduce longwave flux.
$C_{SW} < 0$ clouds increase shortwave albedo.



CLEAR-SKY LONGWAVE RADIATION
ERBS + NOAA9, 2.5 DEG SCANNER, APRIL 1985
GLOBAL MEAN: (60S-60N = 275.8); (90S-90N = 265.8) W/M^2



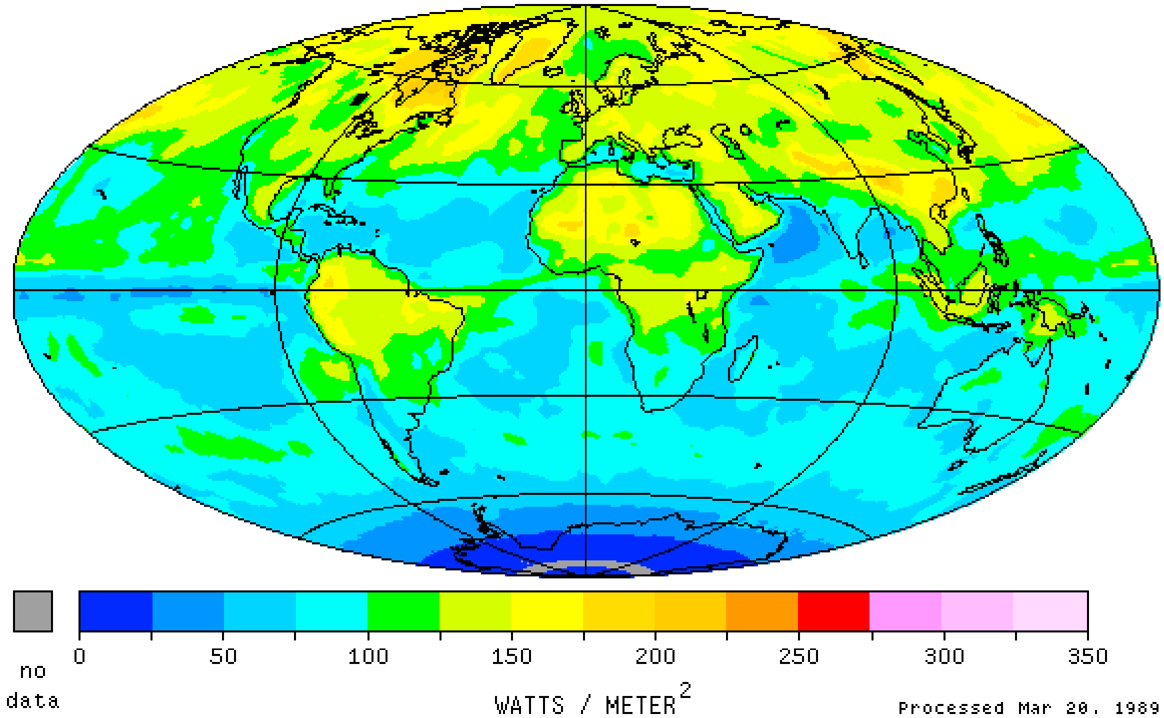
CLEAR-SKY NET RADIATION
ERBS + NOAA9, 2.5 DEG SCANNER, APRIL 1985
GLOBAL MEAN: (60S-60N = 38.7); (90S-90N = 18.4) W/M^2



SHORTWAVE RADIATION

ERBS + NOAA9, 2.5 DEG SCANNER, APRIL 1985

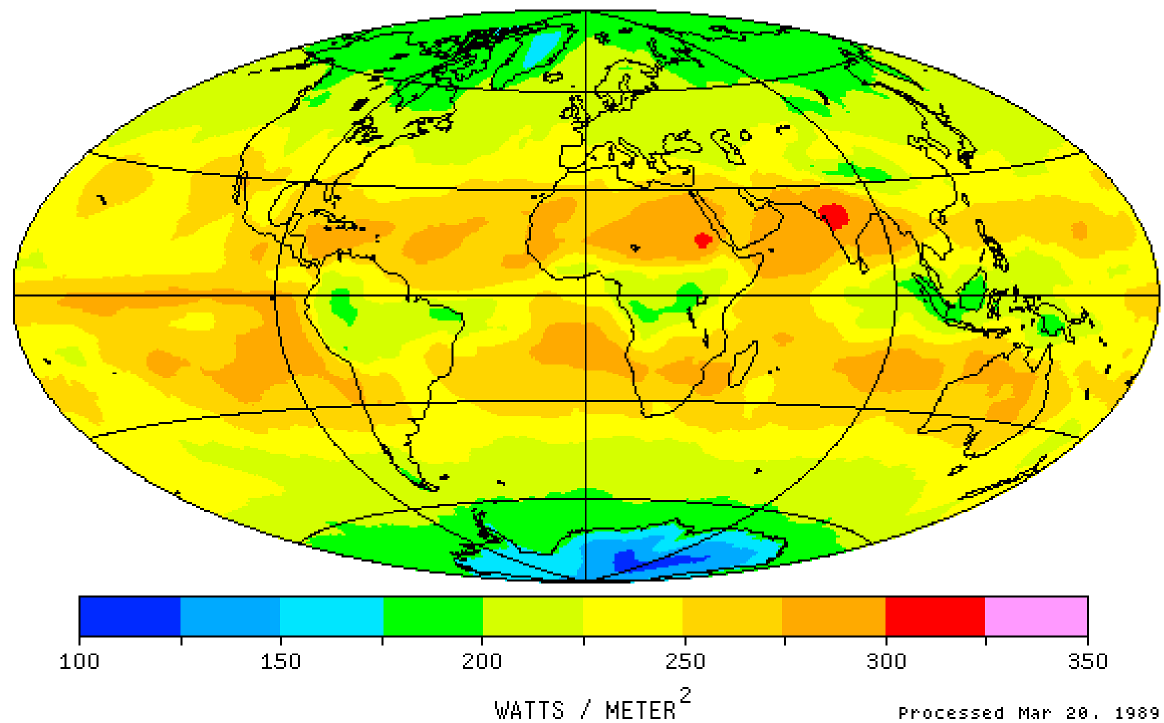
GLOBAL MEAN: (60S-60N = 101.6); (90S-90N = 100.8) W/M^2

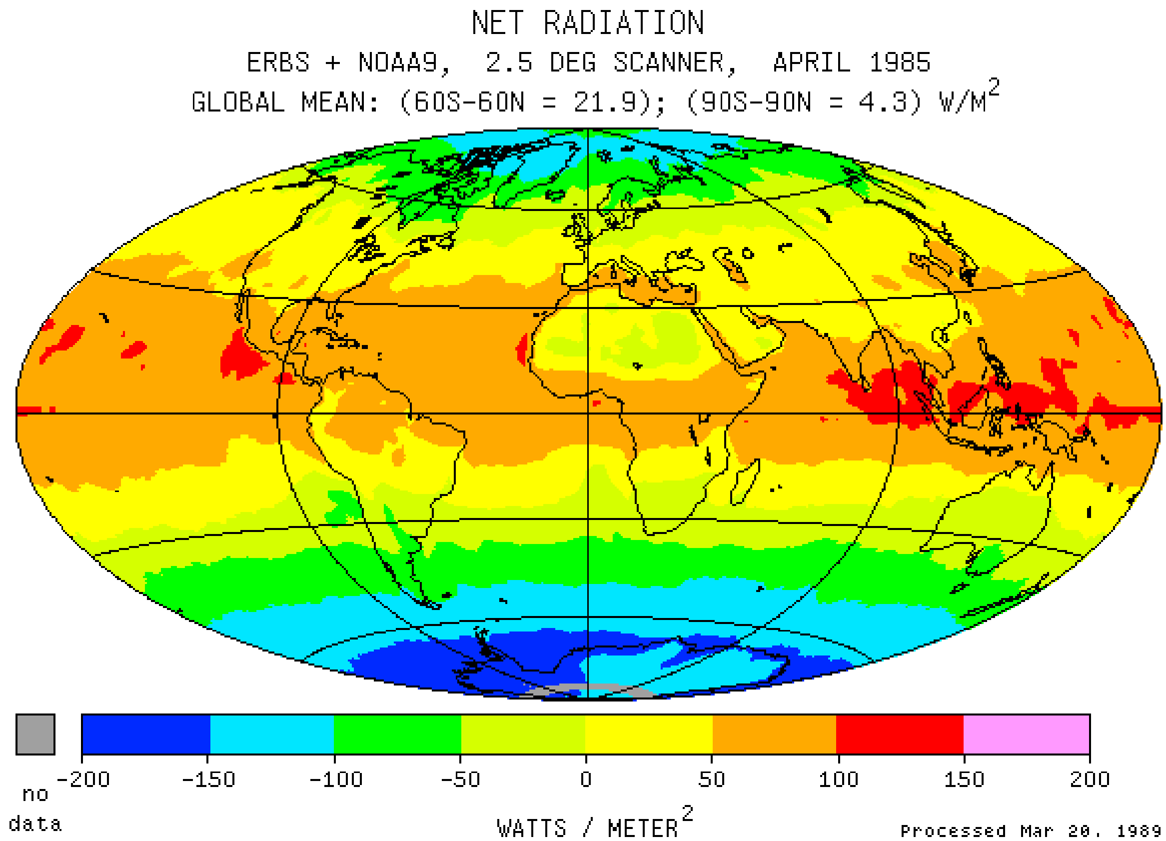


LONGWAVE RADIATION

ERBS + NOAA9, 2.5 DEG SCANNER, APRIL 1985

GLOBAL MEAN: (60S-60N = 242.2); (90S-90N = 234.5) W/M^2





Zonal and Global ERBE Results

Annual absorbed solar flux peaks in tropics, small near poles.

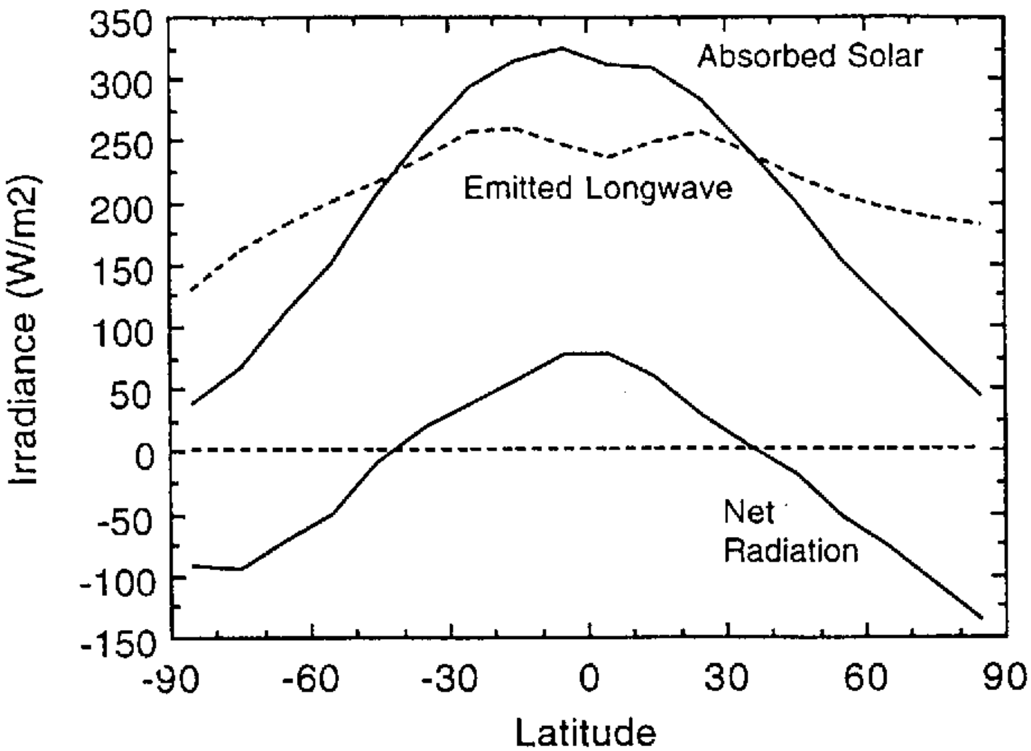
Emitted longwave flux peaks in subtropics, but is more uniform.

Net flux is positive in tropics and negative in mid/high latitudes.
Implies heat transport from equator to poles.

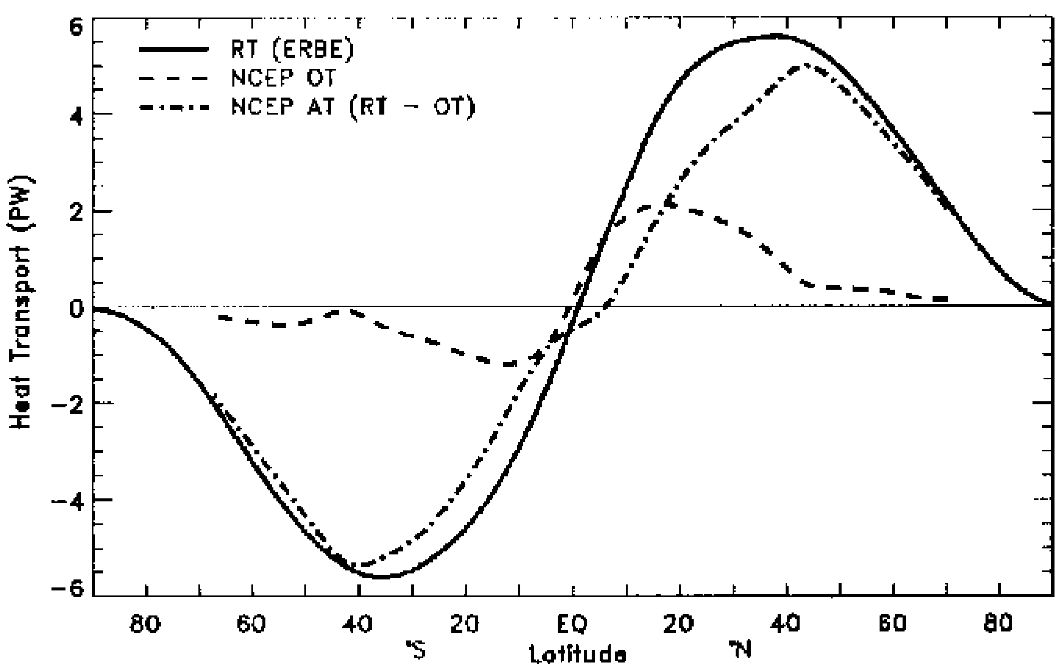
Global energy balance quantifies roles of atmosphere and clouds in the average flows of shortwave and longwave radiation.

Cloud Radiative Forcing from ERBE (W/m^2)

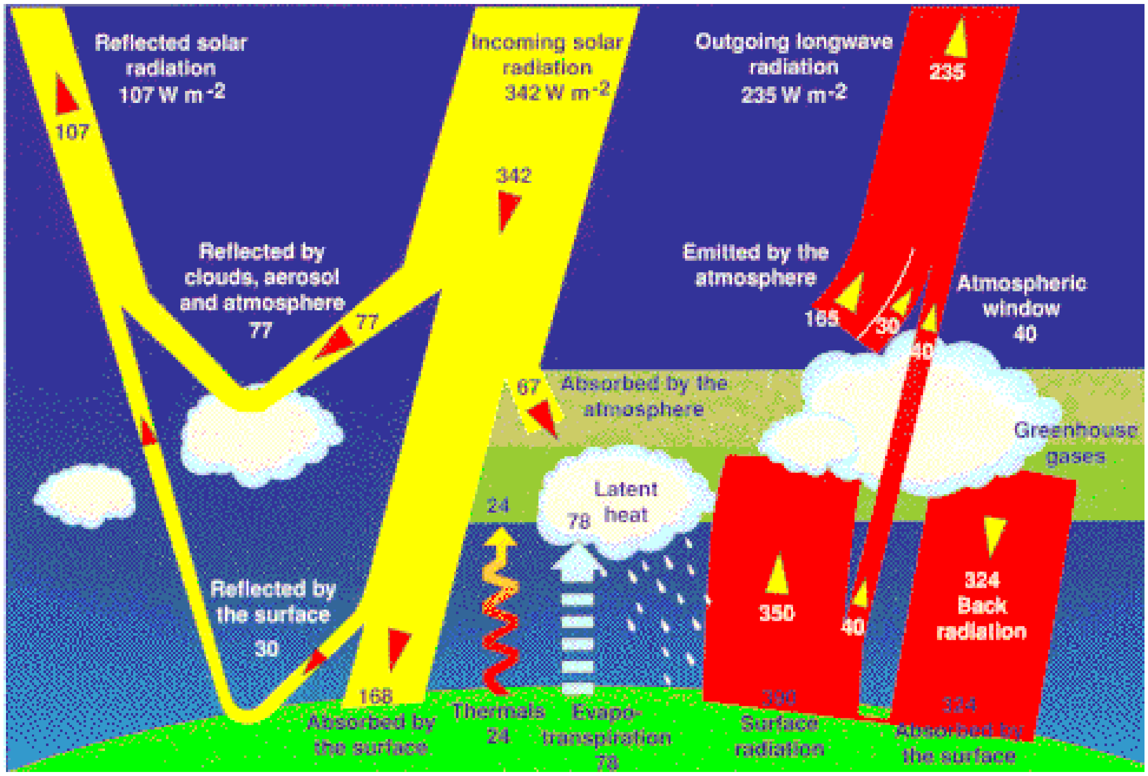
	Average	Cloud-free	Cloud forcing
Outgoing longwave flux	234	266	+31
Absorbed solar flux	239	288	-48
Net radiation	+5	+22	-17
Albedo	30%	15%	+15%



Annual-mean absorbed solar flux, outgoing longwave radiation (OLR), and net radiation averaged around latitude circles.



Total meridonal transport implied by ERBE measurements (RT) and the ocean transport (OT) and implied atmospheric transport (AT) from NCEP reanalysis. [Trenberth and Caron, 2001]



Global annual averaged Earth radiation balance divided into its components.

Current and Future of ERB

CERES is NASA follow on to ERBE:

- Factor of two better spatial resolution and calibration.
- First launch November 1997 on Japanese TRMM spacecraft (power failure after 8 months)
- Two more instruments launched December 1999 on Terra spacecraft.
- Outstanding on-orbit stability ($< 0.5\%$ level).
- Three broadband channels: SW, LW, Window.
- Uses companion imager (VIRS on TRMM; MODIS on Terra) to do vastly improved cloud detection and classification.
- After ~ 2 years of data will build new empirical angular models with order of magnitude more categories.